HIGHER-ORDER QCD CORRECTIONS FOR VECTOR BOSON PRODUCTION AT HADRON COLLIDERS

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We consider higher-order QCD corrections for vector boson production at hadron colliders. We present recent results on transverse-momentum resummation for Z production. Moreover we show numerical results from a new fully exclusive next-to-next-to-leading order (NNLO) calculation.

1 Introduction

The study of vector boson production in hadron collisions, the well know Drell-Yan (DY) process, is nowadays extremely important. Owing to the large production rates and clean experimental signatures of W and Z productions, these processes are standard candles for calibration purposes, they lead to precise determinations of vector boson masses and widths and provide important information on parton distribution functions (pdf). It is therefore essential to have accurate theoretical predictions for vector boson cross section and distributions. This requires the computation of higher-order QCD radiative corrections for such processes.

In these proceedings we present two recent results on higher-order corrections for the DY process: a study of transverse-momentum (q_T) resummation for Z production at the Tevatron [1] and a fully exclusive calculation [2] based on the NNLO subtraction formalism of Ref. [3].

2 Transverse-momentum distribution: fixed-order and resummation

We consider the inclusive hard-scattering process

$$h_1(p_1) + h_2(p_2) \;\rightarrow\; V(M, q_T) + X \;\rightarrow\; l_1 + l_2 + X, \tag{1}$$

where h_1 and h_2 are the colliding hadrons with momenta p_1 and p_2, V is a vector boson (which decays in the lepton pairs l_1, l_2) with invariant mass M and transverse-momentum q_T and X is an arbitrary and undetected final state.

According to the QCD factorization theorem the q_T differential cross section $d\sigma^V/dq_T^2$ can be written as

$$\frac{d\sigma^V}{dq_T^2}(q_T, M, s) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_{a/h_1}(x_1, \mu_F^2)\, f_{b/h_2}(x_2, \mu_F^2)\, \frac{d\hat{\sigma}^V_{ab}}{dq_T^2}(q_T, M, \hat{s}; \alpha_S, \mu_R^2, \mu_F^2)$$

where $f_{a/h}(x, \mu_F^2)$ are the parton densities of the colliding hadrons at the factorization scale μ_F, $d\hat{\sigma}^V_{ab}/dq_T^2$ are the perturbative QCD computable partonic cross sections, s ($\hat{s} = x_1 x_2 s$) is the hadronic (partonic) centre-of-mass energy, and μ_R is the renormalization scale.

In the region where $q_T \sim m_V$, m_V being the mass of the vector boson ($m_V = m_W, m_Z$), the QCD perturbative series is controlled by a small expansion parameter, $\alpha_S(m_V)$, and fixed-order calculations are theoretically justified. In this region, the QCD radiative corrections are known up to next-to-leading order (NLO) [4]. From Fig. 1 we see that the NLO result [1] is in agreement with the experimental data [5] over a wide region of transverse momenta ($q_T \gtrsim 20$ GeV).

In the small-q_T region ($q_T \ll m_V$), the LO and NLO calculations do not describe the data. This is not unexpected since in the small-q_T region the convergence of the fixed-order perturbative expansion is spoiled by the presence of powers of large logarithmic terms, $\alpha_S^n \ln^m(m_V^2/q_T^2)$. To obtain reliable predictions these terms have to be resummed to all orders.

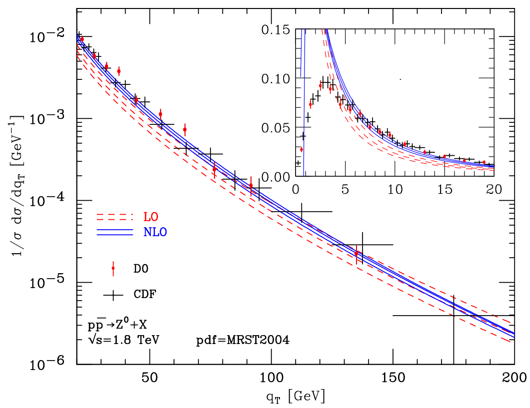


Figure 1: The q_T-spectrum of the Drell-Yan e^+e^- pairs produced in $p\bar{p}$ collisions at the Tevatron Run I. Theoretical results are shown at LO and NLO including the following scale variations: $m_Z/2 \leq \mu_F, \mu_R \leq 2\, m_Z$, with the constraint $1/2 \leq \mu_F/\mu_R \leq 2$.

The resummation is performed at the level of the partonic cross section, which is decomposed as $d\hat{\sigma}_{ab}^V/dq_T^2 = d\hat{\sigma}_{ab}^{V\,(\mathrm{res.})}/dq_T^2 + d\hat{\sigma}_{ab}^{V\,(\mathrm{fin.})}/dq_T^2$. The term $d\hat{\sigma}_{ab}^{V\,(\mathrm{res.})}$ contains all the logarithmically enhanced contributions (at small q_T), which have to be resummed to all orders in α_S, while the term $d\hat{\sigma}_{ab}^{V\,(\mathrm{fin.})}$ is free of such contributions and can be evaluated at fixed order in perturbation theory. Using the Bessel transformation between the conjugate variables q_T and b, the resummed component $d\hat{\sigma}_{ab}^{V\,(\mathrm{res.})}$ can be expressed as

$$\frac{d\hat{\sigma}_{ab}^{V\,(\mathrm{res.})}}{dq_T^2}(q_T, M, \hat{s}, \alpha_S) = \hat{\sigma}_{LO}^V(M)\,\frac{M^2}{\hat{s}}\,\int_0^\infty db\,\frac{b}{2}\,J_0(bq_T)\,\mathcal{W}_{ab}^V(b, M, \hat{s}, \alpha_S)\,, \tag{2}$$

where $\hat{\sigma}_{LO}^V$ is the Born partonic cross section and $J_0(x)$ is the 0-order Bessel function. By taking the N-moments of $\mathcal{W}$ with respect to the variable $z = M^2/\hat{s}$ at fixed M, the resummation structure of $\mathcal{W}_{ab,\,N}^V$ can be organized in the exponential form [a]

$$\mathcal{W}_N^V(b, M, \alpha_S) = \mathcal{H}_N^V(\alpha_S) \times \exp\{\mathcal{G}_N(\alpha_S, L)\}\,, \quad \text{with} \quad L = \ln(Q^2b^2/b_0^2), \quad b_0 = 2e^{-\gamma_E}\,. \tag{3}$$

The scale $Q \sim M \sim m_V$, that appears in the above formula is named resummation scale and it parameterizes the arbitrariness in the resummation procedure. Variations of Q around m_V can be used to estimate the size of higher-order logarithmic contributions that are not explicitly resummed in a given calculation.

The process dependent function $\mathcal{H}_N^V$ includes all the perturbative terms that behave as constants as $q_T \to 0$. It can thus be expanded in powers of $\alpha_S = \alpha_S(\mu_R^2)$:

$$\mathcal{H}_N^V(\alpha_S) = \left[1 + \frac{\alpha_S}{\pi}\,\mathcal{H}_N^{V\,(1)}\left(\frac{\alpha_S}{\pi}\right)^2\,\mathcal{H}_N^{V\,(2)} + \dots\right]. \tag{4}$$

[a] For the sake of simplicity, here we consider only the case of the diagonal terms in the flavour space. For the general case and a detailed discussion of the resummation formalism see Ref. [6].

The universal exponent $\mathcal{G}_N$ contains all the terms that order-by-order in α_S are logarithmically divergent as $b \to \infty$ (i.e. $q_T \to 0$). The logarithmic expansion of $\mathcal{G}_N$ reads

$$\mathcal{G}_N(\alpha_S, L) = L g^{(1)}(\alpha_S L) + g_N^{(2)}(\alpha_S L) + \frac{\alpha_S}{\pi} g_N^{(3)}(\alpha_S L) + \dots \tag{5}$$

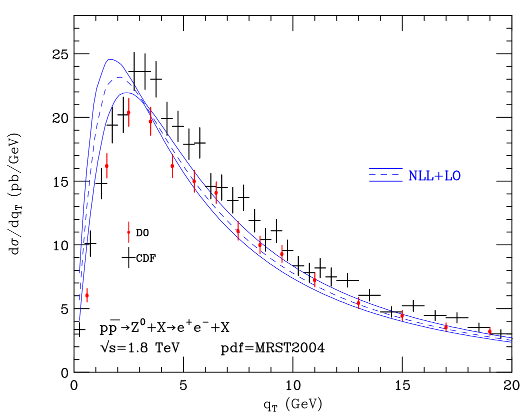
where the term $L\, g^{(1)}$ collects the leading logarithmic (LL) contributions, the function $g_N^{(2)}$ includes the next-to-leading leading logarithmic (NLL) contributions and so forth [b].

Finally the finite component has to be evaluated starting from the usual fixed-order perturbative truncation of the partonic cross section and subtracting the expansion of the resummed part at the same perturbative order: $[d\hat{\sigma}_{ab}^{V\,(\mathrm{fin.})}/dq_T^2]_{f.o.} = [d\hat{\sigma}_{ab}^{V}/dq_T^2]_{f.o.} - [d\hat{\sigma}_{ab}^{V\,(\mathrm{res.})}/dq_T^2]_{f.o.}$. This matching procedure between resummed and finite contributions guarantees to achieve uniform theoretical accuracy over the entire range of transverse momenta.

The inclusion of the functions $g^{(1)}$, $g_N^{(2)}$, $\mathcal{H}_N^{V(1)}$ in the resummed component and of the finite component at LO (i.e. $\mathcal{O}(\alpha_S)$) allows us to perform the resummation at NLL+LO accuracy. The inclusion of the functions $g_N^{(3)}$ and $\mathcal{H}_N^{V(2)}$ and of the finite component at NLO leads to a full NNLL+NLO accuracy. Since the coefficient $\mathcal{H}_N^{V(2)}$ has been computed only recently [2], here we limit ourselves to presenting results up to NLL+LO accuracy.

In Fig. 2 we compare our NLL+LO resummed spectrum [1] (with different values of the factorization, renormalization and resummation scale) with the Tevatron data. We find that the scale uncertainty is about $\pm 12 - 15\%$ from the region of the peak up to the intermediate q_T region ($q_T \sim 20$ GeV), and it is dominated by the resummation-scale uncertainty. Taking into account the scale uncertainty, we see that the resummed curve agrees reasonably well with the experimental points. We expect a sensible reduction of the scale dependence once the complete NNLL+NLO calculation is available.

We note that in Fig. 2 the theoretical results are obtained in a pure perturbative framework, without introducing any models of non-perturbative contributions. These contributions can be relevant in the q_T region below the peak.



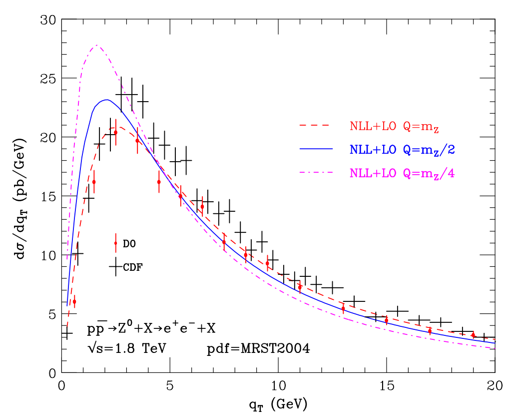


Figure 2: The q_T-spectrum of the Drell-Yan e^+e^- pairs produced in $p\bar{p}$ collisions at the Tevatron Run I. Theoretical results are shown at NLL+LO, including scale variations. Left side: $m_Z/2 \le \mu_F, \mu_R \le 2\, m_Z$, with the constraint $1/2 \le \mu_F/\mu_R \le 2$. Right side: $m_Z/4 \le Q \le m_Z$

[b] To reduce the impact of unjustified higher-order contributions in the large-q_T region, the logarithmic variable L in Eq. (3), which diverges for $b \to 0$, is replaced by $\tilde{L} \equiv \ln\left(Q^2 b^2/b_0^2 + 1\right)$. As a consequence of this replacement, integrating the q_T distribution over q_T we obtain the corresponding total cross section: $\int_0^\infty dq_T^2 (d\hat{\sigma}/dq_T^2)_{NLL+LO} = \hat{\sigma}_{NLO}^{(tot)}$.

3 Fully exclusive NNLO Drell-Yan calculation

We now consider QCD radiative corrections at the fully exclusive level for the process in Eq. 1. The purpose is to compute observables $d\hat{\sigma}^V$, with arbitrary (though infrared safe) kinematical cuts on the final-state leptons and the associated jet activity. Provided the observable is sufficiently inclusive over the small-q_T region, it can reliably be computed at fixed order in perturbation theory.

Following Ref. [3], we observe that, at LO, the transverse momentum q_T of V is exactly zero. This means that if $q_T \neq 0$ the (N)NLO contributions is given by the (N)LO contribution to the final state $V + jet(s)$: $d\hat{\sigma}^V_{(N)NLO}|_{q_T\neq 0} = d\hat{\sigma}^{V+\text{jets}}_{(N)LO}$. We compute $d\hat{\sigma}^{V+\text{jets}}_{NLO}$ by using the subtraction method at NLO and we treat the remaining NNLO singularities at $q_T = 0$ by the additional subtraction of a counter-term [c] constructed by exploiting the universality of the logarithmically-enhanced contributions to the q_T distribution (see Eq. 3)

$$d\hat{\sigma}^V_{(N)NLO} = \mathcal{H}^V_{(N)NLO} \otimes d\hat{\sigma}^V_{LO} + \left[d\hat{\sigma}^{V+\text{jets}}_{(N)LO} - d\hat{\sigma}^{CT}_{(N)LO} \right] \ , \tag{6}$$

where $\mathcal{H}^V_{(N)NLO}$ is the process dependent coefficient function of Eq. 4.

We have encoded our NNLO computation in a parton level Monte Carlo event generator. The calculation includes finite-width effects, the $\gamma - Z$ interference, the leptonic decay of the vector bosons and the corresponding spin correlations. Our numerical code is particularly suitable for the computation of distributions in the form of bin histograms, as shown the illustrative numerical results presented in Fig. 3.

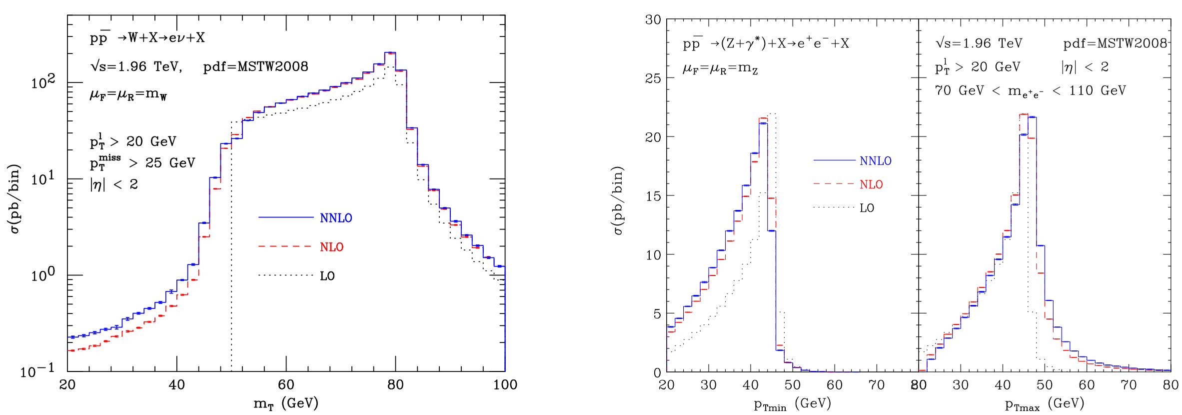


Figure 3: Left side: transverse mass distribution for W production at the Tevatron. Right side: distributions in $p_{T\,min}$ and $p_{T\,max}$ for the Z signal at the Tevatron.

References

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[c] The explicit form of the counter-term $d\hat{\sigma}^{CT}_{(N)LO}$ is given in Ref. [3].